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STUDY OF LOVE AND RAYLEIGH WAVES FROM EARTHQUAKES WITH FAULT PLANE SOLUTIONS OR WITH KNOWN FAULTING

PART 2. APPLICATION OF THE PHASE DIFFERENCE METHOD

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ABSTRACT

The method described in Part 1 of this paper was applied to about 30 earthquakes in various parts of the world. The modified single couple hypothesis proposed in Part 1 appears to explain the observations generally better than the double couple hypothesis. Surprisingly consistent pictures of tectonics were obtained in the Mediterranean region and in Japan on the basis of the modified single couple hypothesis.

Introduction

In the present paper we shall apply the method described in Part 1 to actual earthquakes. We intend to check the validity of the hypothesis on the force system at the source by comparing surface wave observations with theoretical results predicted by the hypothesis using source information based on geological, geodetic and fault plane studies.

A decisive conclusion on the problem may be obtained if we use accurate phase velocity data for the propagation correction. Although the propagation correction is greatly simplified by taking the phase difference between Love and Rayleigh waves as shown in Part 1, the accuracy of the phase velocity data presently available is not yet sufficient to apply our method to an arbitrary wave path on the earth. In this paper, we try to overcome this difficulty by investigating waves from many earthquakes with different source mechanisms but common wave paths. We feel that it is possible to obtain a unique solution, if the source mechanisms of these earthquakes are well known from geological, geodetic and fault plane studies

Earthquakes in the Mediterranean Region

Earthquakes in the Mediterranean region offer excellent materials for the present study, because reliable source information is available such as epicenter location, focal depth and fault-plane solution owing to their proximity to many European stations. These earthquakes usually show well developed Love and Rayleigh waves with periods of 40 to 60 sec on the Pasadena records.

Table 1 shows the list of Mediterranean shocks studied in the present paper. The great circle paths from these shocks to Pasadena are shown in figure 1, on a stereographic projection with Pasadena as the pole. About $\frac{3}{4}$ of the path is within the continents, and the remaining portion lies in the north Atlantic ocean.

The fault-plane solutions are given for five of these shocks by Hodgson and Cock (1956, 1957) and Hodgson and Stevens (1958), and are reproduced in table 2. Hodgson (1963) revised some of the solutions recently, and the revised solutions are also shown in the table. The mechanism of shock M2 was also studied by Di-Filippo and Marcelli (1954). They proposed that the shock might be caused by a sinking.

No fault plane solution has been given for shock M1. This earthquake, however, produced a large fault trace about 50 km long (Richter, 1958). The motion on the fault was right-hand strike-slip. The strike of the fault is about N70°E. This direction is consistent with the initial motion pattern at near stations (Dilgan and Hagiwara, 1956).

The focal depths of these shocks, except for shock M5, are very shallow. Except for shock M5, their epicenter locations were made on the assumption of surface focus in the I. S. S. High intensities and severe damages are reported in the epicen-

TABLE 1
LIST OF MEDITERRANEAN SHOCKS

Shock Number	Date	Origin Time h m s	Epicenter	Distance to Pasadena	Azimuth to Pasadena
M1	March 18, 1953	19 06 13	40°.0N 27°.3E	99°.6	332°
M2	Aug. 12, 1953	9 23 52	38°.3N 20°.8E	98°.5	326°
M3	April 30, 1954	13 02 36	39°.2N 22°.2E	98°.2	328°
M4	July 16, 1955	7 07 10	37°.6N 27°.2E	101°.7	331°
M5	Sept. 12, 1955	6 09 24	32°.2N 29°.6E	107°.4	332°
M6	July 9, 1956	3 11 39	37°N 26°E	101°.7	330°

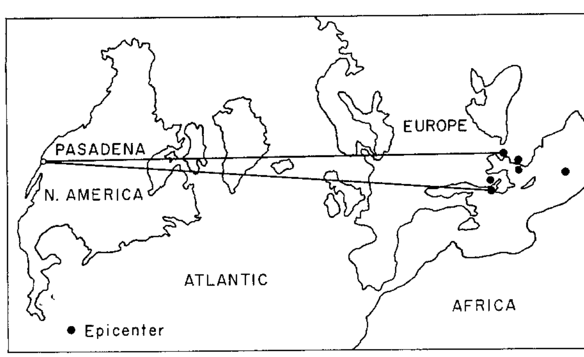


FIG. 1. The great circle paths from Pasadena to the epicenters of the Mediterranean shocks shown on a map of stereographic projection with Pasadena as the pole.

tral areas and there are many near stations reporting P_g arrivals for these shocks. This evidence is further support for shallow foci. Therefore, in computing the source phase and amplitude of Love and Rayleigh waves, we assumed that the depth is zero except for shock M5. In the I.S.S. the depth of M5 is located at the base of superficial layers. We computed, therefore, the source factors of surface waves for $h = 0$ and 0.2λ for this shock.

Theoretical values of the source phase and amplitude of Love and Rayleigh waves in the azimuth to Pasadena are obtained by the use of the table described in Part 1. They are shown in table 3 for the double couple model and the modified single couple model proposed in Part 1. Two sets of values for the modified single couple model correspond to two alternative fault planes of one fault plane solution. The phase values are shown in units of parts of a circle. The phase of Rayleigh waves refers to the radial component, outward from the source being taken positive. The phase of Love waves refers to the transverse displacement, counterclockwise being positive. The source time function is assumed to be a step function. The amplitude values are normalized in the manner described in Part 1 p. 525.

The values for shock M1, for which we have geological evidence only, are computed in the following way. The azimuth to Pasadena from the epicenter of this shock is nearly perpendicular to the strike of the observed fault. If the motion was pure strike-slip as suggested from the geological observations, there will be no Rayleigh waves radiated in the direction to Pasadena. However, Rayleigh waves are fairly well recorded at Pasadena as shown in figure 2. Therefore, we infer that there was a small dip-slip component in the faulting. We computed the phase and amplitude of Love and Rayleigh waves for all possible types of faulting, and found that the phase difference $\phi_R - \phi_L$ between Love and Rayleigh waves is practically

TABLE 2
FAULT PLANE SOLUTIONS OF THE MEDITERRANEAN SHOCKS

Shock Number	Date	Plane *a* (right-lateral)		Plane b (left-lateral)	
		Dip direction	Dip	Dip direction	Dip
M1	March 18, 1953				
M2	Aug. 12, 1953	N27°.5W	71°	S59°W	78°
	(revised)	N135°E	85°	S47°W	74°
M3	April 30, 1954	N4°W	18°	S44°W	78°
	(revised)	N6°W	32°	S55°W	73°
M4	July 16, 1955	N50°W	84°	N40°E	84°
M5	Sept. 12, 1955	N57°W	64°	N52°E	56°
M6	July 9, 1956	N47°W	72°	S28°W	55°

independent of both slip and dip angle for this particular azimuth once the type of faulting is determined. Table 4 lists the values of $\phi_R - \phi_L$ for four types of faulting on the fault with a dip angle of 60°. As will be shown later, the observed value of $\phi_R - \phi_L$ for this shock is 0.36 and does not agree with any of the theoretical values corresponding to the case of reverse faulting. Therefore, we listed in table 3 the phase and amplitude values corresponding to the cases of normal faulting with the fault planes dipping north (plane a) and south (plane b), where the slip angle is assumed as 12°.

The records of Love and Rayleigh waves from these shocks obtained by the Benioff long period seismograph ($T_0 = 1$ sec, $T_g = 90$ sec) at Pasadena are shown in figure 2. Both waves show well dispersed wave trains, and justify the use of stationary phase technique to obtain their source phases. The propagation correction was made on the assumption that the portion of wave path within the ocean is 25°, and the rest is within the continent. The phase velocity values used are those of Case 122 for ocean and Case 6EG for continents, as given in table 1 of Part 1. The source phase differences $\phi_R - \phi_L$ are shown for shocks M1, M3, M4 and M5 for various periods in table 5. They were not obtained for shocks M2 and M6,

TABLE 3

THEORETICAL SOURCE PHASE AND AMPLITUDE OF LOVE AND RAYLEIGH WAVES IN THE AZIMUTH TO PASADENA FOR THE MEDITERRANEAN SHOCKS ON THE ASSUMPTION OF THE DOUBLE COUPLE AND THE MODIFIED SINGLE COUPLE

(The units of ϕ_R and ϕ_L are parts of circle.)

Shock Number	Date	Depth	Modified Single Couple										Double Couple					Observed $\phi_R-\phi_L$
			Plane *a*					Plane *b*										
			A_R	A_L	ϕ_R	ϕ_L	$\phi_R-\phi_L$	A_R	A_L	ϕ_R	ϕ_L	$\phi_R-\phi_L$	A_R	A_L	ϕ_R	ϕ_L	$\phi_R-\phi_L$	
M1	1953 March 18	0	.23	.60	.68	.36	.32	.26	.59	.03	.38	.65	.17	.60	.88	.37	.51	.36
M2	1953 August 12	0	.15	.63	.57	.37	.20	.11	.63	.16	.58	.78	.02	.63	.58	.37	.21	
	(revised)		.33	.63	.00	.37	.63	.34	.62	.75	.38	.37	.21	.63	.88	.38		
M3	1954 April 30	0	.23	.17	.63	.31	.32	.26	.19	.06	.38	.68	.17	.23	.88	.33	.55	.66
	(revised)		.29	.29	.63	.33	.30	.33	.30	.04	.38	.66	.22	.34	.88	.35		
M4	1955 July 16	0	.46	.54	.90	.38	.52	.46	.54	.85	.38	.47	.45	.54	.87	.38	.49	.52
M5	1955 Sept. 12	0	.46	.32	.04	.36	.68	.41	.43	.67	.38	.29	.04	.40	.88	.37	.51	.25
		0.2λ	.44		.11	.35	.76	.07		.73	.39	.34	.39		.09	.37	.72	
M6	1956 July 9	0	.86	.35	.73	.37	.36	.91	.24	.01	.37	.64	.68	.31	.88	.36	.52	
Kern County	1952 July 21	0						.56	.27	.55	.38	.17	.38	.35	.38	.36	.02	.165

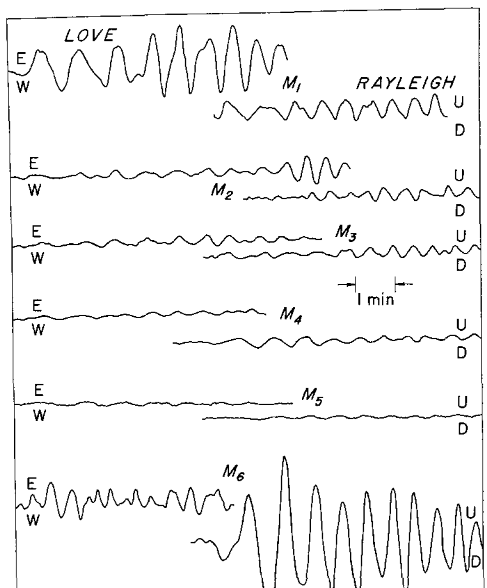


FIG. 2. Records of Love and Rayleigh waves from the Mediterranean shocks obtained at Pasadena by the Benioff long period seismograph (T_0 = 1 sec, T_g = 90 sec).

because Rayleigh waves were poorly recorded for M2 and Love waves were poorly recorded for M6. These observed facts are consistent with the theory based on the fault plane solutions as seen in table 3, where smaller amplitudes of Rayleigh waves for M2 (0.02 to 0.3 for Rayleigh compared to 0.63 for Love waves) and smaller amplitudes of Love waves for M6 (0.24 to 0.35 for Love waves compared to 0.68 to 0.91 for Rayleigh waves) are indicated. (It is difficult to explain observed

TABLE 4

THE VALUES OF $\phi_R - \phi_L$ FOR SHOCK M1 ON DIFFERENT ASSUMPTIONS ABOUT DIP DIRECTION

(in parts of a circle)

	$\phi_R - \phi_L$			
	Right-lateral normal		Right-lateral reverse	
	Dip north	Dip south	Dip north	Dip south
Double couple	0.51	0.49	0.01	0.99
Modified single couple	0.32	0.68	0.82	0.18

TABLE 5

OBSERVED VALUES OF $\phi_R - \phi_L$ FOR THE MEDITERRANEAN SHOCKS

(in parts of a circle)

Shock Number / Date	M1 March 18, 1953	M3 April 30, 1954	M4 July 16, 1955	M5 Sept. 12, 1955
Period, sec				
44	0.43	0.68	0.56	0.27
46	0.36	0.67	0.47	0.23
48	0.39	0.60	0.54	0.29
50	0.38	0.66	0.50	0.24
52	0.34	0.67	0.50	0.25
54	0.35	0.65	0.50	0.25
56	0.33	0.70	0.53	0.26
58	0.32		0.50	0.24
60	0.32		0.55	
Average	0.36	0.66	0.52	0.25

strong Love waves from shock M2, if the source is a sinking as proposed by DiFilippo and Marcelli.)

A comparison of theoretical and observed values of $\phi_R - \phi_L$ is shown in figure 3. The range of the theoretical value for shock M5 indicates the uncertainty in the focal depth. We see a surprisingly good agreement between the observation and the theory based on the modified single couple hypothesis. One of the two theoretical values for each shock shows practically the same value as the corresponding observed one. On the other hand, the agreement is poor for the hypothesis of double couple. This result strongly supports the modified single couple as the equivalent force system of the earthquake source.

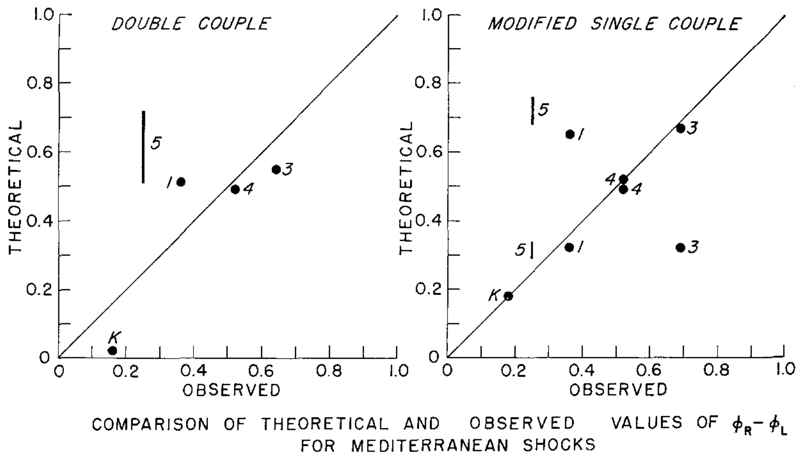


FIG. 3. Comparison of theoretical and observed values of $\phi_R - \phi_L$ for the Mediterranean shocks on the assumption of the double couple and the modified single couple. (The units are parts of a circle.) The numbers correspond to those shown in table 1. K refers to the Kern County main shock.

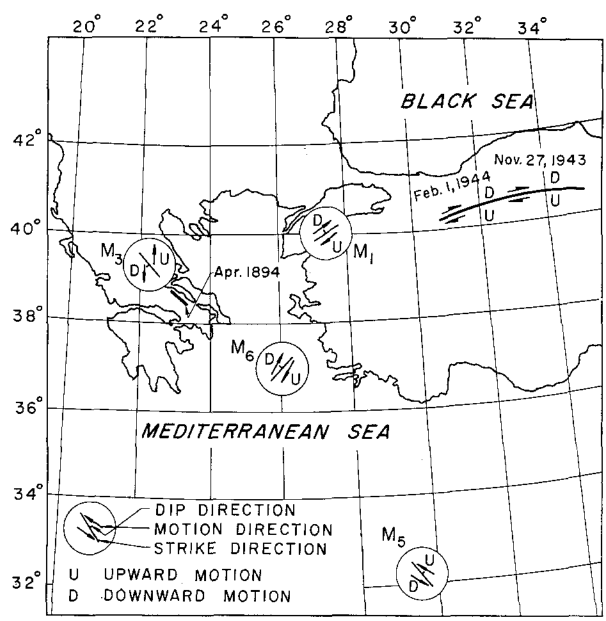


FIG. 4. Fault plane solutions determined with the aid of surface wave evidence on the assumption of the modified single couple. The numbers correspond to those shown in table 1.

Further, we get a consistent picture of tectonics in the Mediterranean region when we choose between the two fault planes of each fault plane solution on the basis of the modified single couple hypothesis. As shown in table 3, the plane *a* gives agreement between theory and observation for shock M1, and the plane *b* gives agreement for M3 and M5. It is not possible to choose between two planes of

M4, because the source of this shock is almost pure strike-slip on a nearly vertical fault and two planes give practically the same phase values.

Since it was impossible to find the value of $\phi_R - \phi_L$ for shock M6 because of poor Love waves, we made a comparative study of Rayleigh waves from this shock and those from shock M4, which occurred almost at the same place as M6. The source phase difference between the two shocks is obtained by a cross-correlation method in the following way. First, both records are put into a filter which makes the amplitude spectrum flat without phase distortion in the period range 35 to 70 sec. Then, the cross-correlation function is computed between them and is shown in figure 5. The shape of this function indicates that the Rayleigh waves from M4 have the phase angle slightly advanced relative to that for M6. In other words, the phase value should be slightly greater for M4 than for M6.

The theoretical phase values of Rayleigh waves from these shocks are shown in table 3. The value for M4 lies between 0.85 and 0.90 circle for any choice of the source type. On the other hand, the value for M6 is 0.73 or 0.01 for the modified single couple model and 0.88 for the double couple. Again, we see an excellent agree-

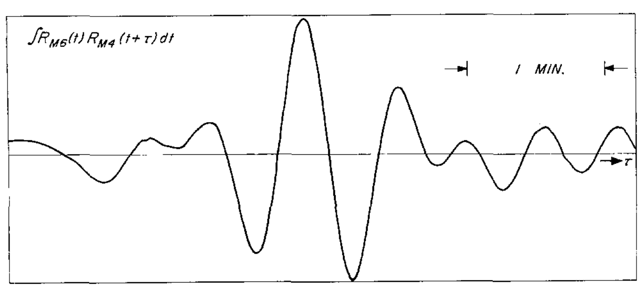


FIG. 5. Cross-correlation function between Rayleigh waves of shock $M4$ and $M6$.

ment between the theory and observation if we take the fault plane which gives the phase value of 0.73 on the assumption of the modified single couple. Thus, the plane a is preferred for this shock.

The fault planes thus preferred on the assumption of the modified single couple are shown on a map in figure 4. The faults observed in some other earthquakes in the region are also shown schematically (cf. Richter, 1958). The fault strikes and motion directions in these earthquakes show remarkable consistent features. There seem to be two structural trends in this region. One runs in the E-W direction in northern Turkey and bends to the SW direction into the Mediterranean Sea. On the faults along this zone, the motion is right-lateral and downthrow is on the north side. The other zone trends NW-SE from Greece into the Mediterranean Sea. On the faults along this zone, the motion is left-lateral and downthrow is on the southwest side. These features seem to be consistent with the results of geological studies in this region. For instance, Pavoni (1961) describes the tectonics in northern Turkey and emphasizes the importance of right-lateral motion along faults running in E-W direction. On the other hand, major faults trends NW-SE in Greece as may be seen in a paper by Galanopoulos (1963), who showed a strong correlation between the seismic activity and the surface geology in this region.

Kern County Earthquake of 1952

The records of the Kern County earthquake of 1952 obtained at several European stations provide good material to check the validity of conclusions obtained in the preceding section. The fault plane solution of this earthquake was given by Gutenberg (1955) based on P waves, S waves and geological evidence. The wave paths to some of the European stations are nearly the same as those studied in the preceding section, and we can use the same phase velocity data as used earlier in obtaining the propagation correction.

The records of this earthquake were previously collected at the Seismological Laboratory, Pasadena by Dr. Beno Gutenberg from many stations of the World. The records obtained by the 3 component Wiechert seismographs at Triest, Zagreb,

TABLE 6

Observed Values of $\phi_R - \phi_L$ for the Kern County Earthquake of 1952 Obtained at some European Stations

	Triest	Zagreb	Beograd	Athens
Δ	89.1°	89.9°	92.5°	99.6°
φ	31°	30°	28°	30°
T (sec)	$\phi_R - \phi_L$ (in parts of a circle)			
42	−0.02	0.17	0.05	−0.09
44	0.12	0.16	0.10	0.10
46	0.22	0.11	0.14	0.11
48	0.28	0.11	0.13	0.09
50	0.34	0.22	0.18	0.0
52	0.37	0.25	0.20	0.0
54		0.30	0.19	−0.02
56		0.31	0.20	
58		0.30	0.19	
60		0.29	0.19	
62		0.28	0.20	

$\overline{\phi_R - \phi_L} = 0.165$

Beograd and Athens are used in this study. Table 6 shows the epicentral distances and the azimuthal angles to these stations. The table also lists the observed values of $\phi_R - \phi_L$ obtained by the stationary phase technique. The average value over all stations is obtained as 0.165 in parts of a circle.

According to Gutenberg (1955), the source of this earthquake is a left lateral reverse movement on a fault with strike direction N50°E and dip angle 63°. He was able to determine the fault plane uniquely, because both geological and geodetic investigations revealed the fault traces running in the direction N50°E. Based on this solution, we obtained the phase and amplitude of Love and Rayleigh waves in the azimuth to these stations. Since the fault plane is predetermined, we get only one set of values in this case under the modified single couple assumption, as shown in table 3. The theoretical value of $\phi_R - \phi_L$ is 0.17 for the modified single couple and 0.02 for the double couple. (Part 3 of this paper describes how these values are obtained.)

We see, again, a perfect agreement between theory and observation on the assumption of modified single couple. This result supports the validity of the phase velocity data used in the propagation correction and consequently the conclusions obtained in the preceding section.

Aftershocks of the Kern County Earthquake

The source mechanism of some of the aftershocks of the Kern County earthquake of 1952 was studied by Aki (1960a, b, 1962b) by the use of Love and Rayleigh waves, and the result was compared with the result from initial motion data. We shall, in this section, make a more detailed comparison by applying our new method to the records at Weston, Massachusetts from those shocks listed in table 7. Their epicenters and origin times were given by Richter (1955), and their depths were given by Cisternas (1963). The latter author believes that the accuracy of the depth determination is 2 to 3 kilometers.

TABLE 7
List of the Kern County Aftershocks

Shock No.	Date Time (h. m.)	Lat. Long. (deg. min.)	Depth (km)	Nodal Lines	Distance	Azimuth
					to Weston	
75	July 23, 1952 00:39	35:22 118:35	0	N50°E (SE side down)	37.1°	64.5°
117	July 25, 1952 19:10	35:19 118:30	21	N42°E (left-lateral) N39°W (right-lateral)	37.0°	64.5°
118	July 25, 1952 19:43	35:19 118:30	5	N31°E (left-lateral) N22°W (right-lateral)	37.0°	64.5°

The information from initial motions are not complete for these shocks. Only nodal lines at near stations are given by Båth and Richter (1958) as shown in table 7. It will, however, be shown that there will be not much variation in the source phase difference $\phi_R - \phi_L$ for particular azimuths due to the variation in source parameters, once the nodal lines are fixed.

There is an awkward problem with the use of nodal lines at near stations. If the fault plane is vertical, the nodal lines of initial motion will be parallel to the strike of the plane. However, if the fault plane dips, the nodal line beyond the critical distance (at which the initial motion become the refracted waves P_n) will no longer be parallel to the strike. The deviation of the nodal line from the strike direction depends on the focal depth, the crustal structure and the dip angle of the plane (Kawasumi, 1934). Since the data are not sufficient to permit the computation of the exact deviation, we assumed that the nodal lines approximately represent the strike directions of fault planes.

Table 8 shows the phase difference $\phi_R - \phi_L$ in the azimuth to Weston for shock No. 118 for various fault systems with given nodal lines. It can be seen that if the dip direction is fixed, the value of $\phi_R - \phi_L$ varies only slightly with the assumed dip angle for this particular azimuth, and that the value is either in the range 0.27 to 0.34 or in the range 0.66 to 0.73 for the modified single couple model, and in the range 0.45 to 0.55 for the double couple model. We show this range of variation in figure 6, where the theoretical values are compared to the observed values.

As shown in table 8, under the assumption of the modified single couple, the right lateral solution with the fault dipping east gives nearly the same value of $\phi_R - \phi_L$ as the left lateral solution with the fault dipping east. Therefore, we cannot choose the actual fault between two fault planes when only nodal lines at near stations are given from initial motion data.

The theoretical values for shock No. 117 are computed in the same way. Since the depth of this shock is greater than others, we computed the values for the depth of 0.2 of the wavelength. The actual depth reported by Cisternas is 21 km, which

TABLE 8

THEORETICAL VALUES OF $\phi_R - \phi_L$ FOR SHOCK NO. 118 ON DIFFERENT ASSUMPTIONS ABOUT DIP DIRECTION AND DIP ANGLE

(in parts of a circle)

	Dip	Modified Single Couple						Double Couple					
		80	70	60	50	40	30	80	70	60	50	40	30
Right-lateral solution	Dip east	0.27	0.29	0.30	0.31	0.32	0.33	0.49	0.50	0.51	0.51	0.52	0.52
	Dip west	0.73	0.71	0.70	0.69	0.68	0.67	0.51	0.50	0.49	0.49	0.48	0.48
Left-lateral solution	Dip east	0.31	0.33	0.34	0.34	0.33	0.31	0.45	0.48	0.49	0.49	0.49	0.50
	Dip west	0.69	0.67	0.66	0.66	0.67	0.69	0.55	0.52	0.51	0.51	0.51	0.50

is approximately 0.2 of the wavelength studied. The range of theoretical values for this shock is also shown in figure 6.

The shock No. 75 shows only one nodal line. Båth and Richter (1958) interpreted this shock as a dip-slip, downthrow on the southeast side. If only one nodal line exists for the entire earth's surface, the source should be the pure dip-slip on a vertical fault. Theoretically, this type of fault does not generate Love waves if the modified single couple is assumed, and does not generate Rayleigh waves in the case of surface focus if the double couple is assumed. Since both Love and Rayleigh waves are actually observed, it is unlikely that the source is pure dip-slip on a vertical fault. We computed the source phase difference $\phi_R - \phi_L$ for two possible cases; a pure dip-slip on a slightly dipping fault and a small strike-slip component on a vertical fault. It is found that the phase and amplitude of Love and Rayleigh waves in the azimuth to Weston are roughly the same for the above two cases. The values of $\phi_R - \phi_L$ are shown in table 9 for these cases. The range of variation in the values shown in figure 6 correspond to the range of dip angle 70° to 85° for the pure dip-slip source.

The observed values of $\phi_R - \phi_L$ are obtained by the band-pass filtering and correlation method described in Part 1. The correlation coefficients between radial and vertical components of Rayleigh waves, which are computed to check the contamination of noises, show satisfactorily high values: 0.84, 0.72 and 0.80 for shocks No. 75, 118 and 117 respectively. The cross-correlation functions between Love and Rayleigh waves are shown in figure 7. The source phase difference $\Delta\phi = \phi_R - \phi_L$ is obtained by the use of equation 14 of Part 1 as 0.17, 0.23 and 0.60 in parts of a circle for the shocks No. 117, 118 and 75 respectively. In the propagation correction,

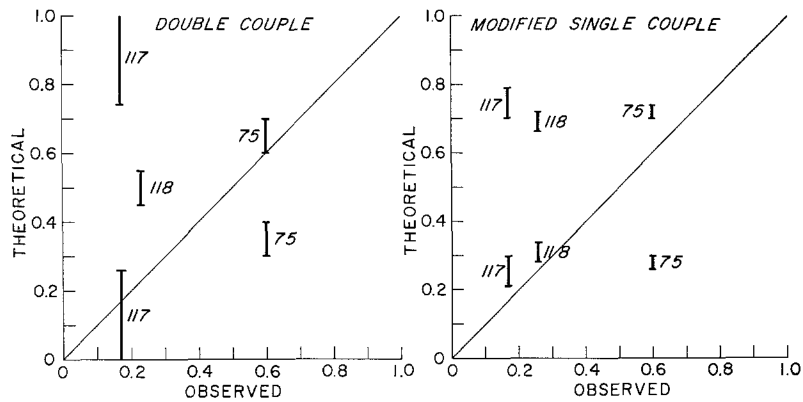


FIG. 6. Comparison of theoretical and observed values of $\phi_R - \phi_L$ for the Kern County aftershocks on the assumption of the double couple and the modified single couple. (The units are parts of a circle.)

TABLE 9

THEORETICAL VALUES OF $\phi_R - \phi_L$ FOR SHOCK NO. 75 ON DIFFERENT ASSUMPTIONS ABOUT FAULT MOTION

(in parts of a circle)

	$\phi_R - \phi_L$			
	Pure dip-slip		Small strike-slip	
	Dip-east Dip = 80°	Dip-west dip = 80°	Right slip = 80°	Left slip = 80°
Double couple	0.36	0.64	0.58	0.42
Modified single couple	0.30	0.70	0.71	0.29

the phase velocity data for Alexander's case are used for the first 1000 km from the epicenter to Weston, and those for Case 6EG are used for the rest of the wave path (cf. table 1 of Part 1).

The comparison of the theoretical and observed values of $\phi_R - \phi_L$ is made in figure 6 for the double couple model and the modified single couple model. We see that one of the theoretical values computed under the assumption of the modified single couple agrees well with the observed value for all of the shocks if we add 0.10 to the observed values. This corresponds to the revision of phase delay time used in the propagation correction by about 0.08 sec per 100 km, which is permissible in view of the accuracy of dispersion data presently available. We must add this amount to the phase delay time difference $(1/C_R) - (1/C_L)$ used in the propagation correction. On the other hand, it is difficult to get perfect agreement between the theory and observation if we assume the double couple hypothesis, no matter how we revise the phase velocity data.

Other evidence is available to support the hypothesis of modified single couple, namely, the absolute values of source phase of Rayleigh and Love waves. The

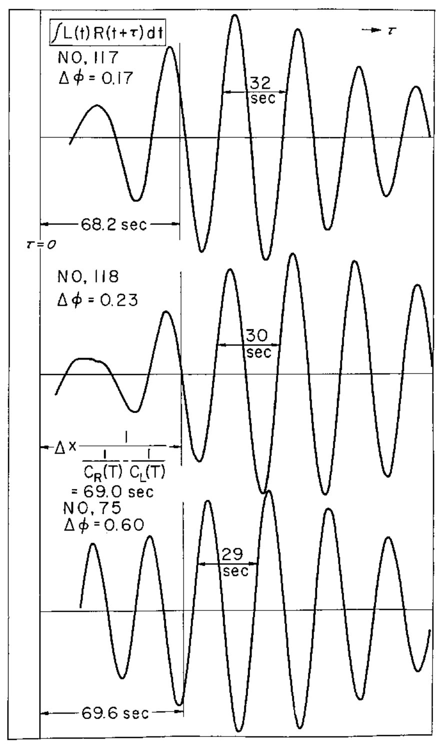


FIG. 7. Crosscorrelation function between Love and Rayleigh waves in the period band from 27 to 40 sec obtained from the Weston records of the Kern County aftershocks. The method of obtaining the value of $\phi_R - \phi_L$ (designated as $\Delta\phi$ in this figure) from the crosscorrelation function is given in Part 1 of this paper (cf. equation 14).

theoretical phase and amplitude of Love and Rayleigh waves for these shocks are shown in table 10. These values correspond to the fault systems which give the best fit to the observed $\phi_R - \phi_L$ values. From previous studies (Aki, 1960a, 1960b), we know that the source phases of Love waves for No. 117 and No. 118 are the same and different by 0.5 circle from that for No. 75. The theoretical values for the modified single couple (ϕ_L = 0.37, 0.38 and 0.89 for No. 118, 117 and 75 respectively) agree excellently with this observation and they agree fairly well also for the double couple. The phases of Rayleigh waves were found to be nearly the same for all of these shocks by comparison of their source functions (Aki, 1960b). The theoretical values for the modified single couple agree with this observation (ϕ_R = 0.71, 0.60 and 0.59 for No. 118, 117 and 75 respectively). On the other hand, the double couple hypothesis gives a phase value for No. 75 different from those for the others by 0.2 to 0.5 circle. This is clearly inconsistent with the observation.

Earthquakes in and Near Japan

Japan and its vicinity is another region where we can find many earthquakes with reliable source information available from geological, geodetic and seismological

TABLE 10

Theoretical Source Phase and Amplitude of Love and Rayleigh Waves for the Kern County Aftershocks on the Assumption of the Double Couple and the Modified Single Couple

(The units of ϕ_R and ϕ_L are parts of a circle)

Shock Number		h	A_R	A_L	ϕ_R	ϕ_L	$\phi_R - \phi_L$	$\phi_R - \phi_L$ (observed)
	Modified Single Couple							
118	Left-lateral dip east dip = 60°	0	0.78	0.26	0.71	0.37	0.34	0.23
117	Left-lateral dip east dip = 70°	0 0.2λ	0.63 0.22	0.49	0.74 0.60	0.38 0.38	0.36 0.22	0.17
75	Pure dip-slip dip west dip = 80°	0	0.27	0.03	0.59	0.89	0.70	0.60
	Double Couple							
118	Left-lateral dip-east dip = 80°	0	0.25	0.18	0.88	0.43	0.45	0.23
117	Left-lateral dip-west dip = 70°	0 0.2λ	0.47 0.14	0.52	0.88 0.56	0.37 0.36	0.51 0.20	0.17
75	Pure dip-slip dip-west dip = 80°	0	0.10	0.09	0.38	0.74	0.64	0.60

studies. Table 11 lists the shocks studied in this section. All of them showed well recorded Love and Rayleigh waves at Pasadena on the Benioff long period seismograph ($T_0 = 1$ sec. $T_g = 90$ sec), and/or by the Benioff strain seismograph ($T_g = 70$ sec), and/or by the Press-Ewing seismograph ($T_0 = 30$ sec, $T_g = 90$ sec). Well defined faults were found in four of these shocks by geological and geodetic investigations. Fault plane solutions were given for nine of them based on initial motion data. For the rest of the shocks, the nodal lines of the initial motions are clearly defined from the near station data. This information is summarized in table 12.

The great circle paths from the epicenters of these shocks to Pasadena are shown in figure 8 on a map of stereographic projection with Pasadena as the pole. Their paths lie mostly in the north Pacific ocean near continental boundaries. Despite their proximity to the continental boundary, we can safely assume that the propagation characteristics in the oceanic portion of the path is common for all of these shocks, at least for the difference between Love and Rayleigh waves, because it was found by Aki and Kaminuma (1963) and Kaminuma and Aki (1963) that the wave fronts of Love and Rayleigh waves from the Aleutian shock of March 9, 1957 show only a small deviation from the equal epicentral lines within Japan, and that the

TABLE 11

LIST OF THE SHOCKS IN AND NEAR JAPAN

No.	Name	Date	Origin Time (G. C. T.) h m s	Latitude	Longitude	Focal Depth, km	Epicentral Distance to Pasadena, km	Path Wthin Continent, km	Azimuth to Pasadena
1		May 23, 1938	07 18 28	36.5°N	141.6°E	Surface	8640	20	N57°E
2	Tottori	Sept. 10, 1943	08 36 54	35.6°N	134.2°E	10	9242	940	N52°E
3	Mikawa	Jan. 12, 1945	18 38 24	34.8°N	137.0°E	Surface	9096	620	N54°E
4		April 17, 1948	16 11 28	33.0°N	135.6°E	40	9319	690	N53°E
5	Fukui	June 28, 1948	07 13 27	36.1°N	136.2°E	33	9065	730	N53°E
6	Hualien (Taiwan)	Oct. 22, 1951	03 29 26	23.9°N	121.7°E	Surface	10980	1350	N47°E
7	Longitudinal Valley (Taiwan)	Nov. 24, 1951	18 47 13	22.9°N	121.5°E	Surface	11100	1350	N47°E
8	Daishoji	March 7, 1952	07 32 43	36.4°N	136.2°E	20 (base of superficial layers)	9045	730	N53°E
9	Yoshino	July 17, 1952	16 09 50	34.4°N	135.8°E	70	9207	780	N53°E
10		Aug. 12, 1956	16 59 31	33.8°N	138.8°E	40–60	9015	150	N57°E
11		Sept. 29, 1956	23 20 52	35.5°N	140.0°E	60	8828	190	N56°E
12	(Taiwan)	Feb. 23, 1957	20 26 12	24°N	122°E	0	10980	1350	N47°E
13		Nov. 10, 1957	19 20 05	34.3°N	139.3°E	5	8953	250	N55°E
14		Nov. 12, 1958	20 23 26	44.5°N	148.5°E	0.01 R	7689	250	N62°E
15		Jan. 22, 1959	05 10 28	37.5°N	142.3°E	30	8484	30	N57°E
16	Odaigahara	Dec. 26, 1960	01 44 46	34.2°N	136.2°E	60	9195	680	N54°E
17		Jan. 16, 1961	07 20 05	36.0°N	142.3°E	40	8624	0	N57°E
18	Kitamino	Aug. 19, 1961	05 33 30	36.0°N	136.8°E	0	8833 (to Tinnemaha)	600	N52°E (to Tinnemaha)

deviation is nearly the same for Love and Rayleigh waves. Since the wave path from the Aleutians to Japan lies closer to the continental boundary than the path from Pasadena, the effect of the boundary should be smaller on the latter path and may be neglected.

In the propagation correction, we use the phase velocity data from Case 6EJ (Aki, 1961) for the portion of the wave path within Japan. For the oceanic portion of the path, instead of using the standard values described in the previous sections, we used new values which are determined in the following way. We take two earthquakes, shocks No. 2 and No. 5, for which the faulting in the epicentral area was carefully studied by geological and geodetic methods. Then, we compute the source phase difference $\phi_R - \phi_L$ on the basis of the observed faulting. Finally, we determine the propagation correction which gives the observed phase difference in agreement with the theoretical.

The fault in shock No. 2 (Tottori earthquake) was studied by Tsuya (1944). He showed that the fault consists of 3 branches, for each of which the character of faulting is summarized in table 12. The source phase and amplitude of Love and Rayleigh waves from each branch in the azimuth to Pasadena are shown in table 13. We synthesized contributions from these branches by assuming that each branch generated the waves at the same time and place with the same magnitude of force system. This simple synthesis is justified in this case, because the wavelength (120 km $\sim$ 280 km) is much greater than the distances (2 $\sim$ 5 km) between the branches and also because the phase values for both waves are not much different among them, and their contributions tend to add to each other rather than to cancel. The result of synthesis is also shown in table 13.

The fault in shock No. 5 (Fukui earthquake) was discovered by precise leveling and triangulation. Since the dip angle of the fault was not determined by these observations, we computed the source phase and amplitude of Love and Rayleigh

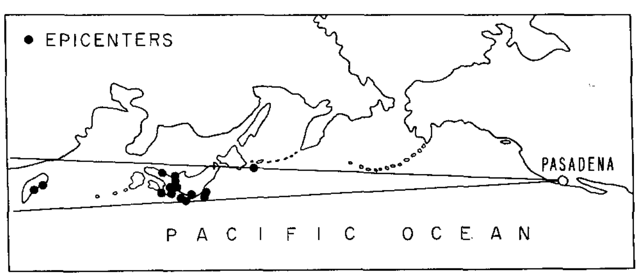


FIG. 8. The great circle paths from Pasadena to the epicenters of the Japanese shocks shown on a map of stereographic projection with Pasadena as the pole.

waves for three cases with different dips. The result (table 13) shows that they do not depend much on the dip angle if the motion direction is fixed from the geodetic observation. The focal depth of this shock was reported as 33 km (Tsuya, 1950). Since the fault was evidenced at the surface, the effective depth must be shallower than 33 km. We computed the source values of surface waves for the depths 0.0 and 0.2 of wavelength. The difference between the two depths is small as shown in table 13, and we take the average value of them as representing the theoretical value for this shock.

The initial motions from these two shocks show quadrantal patterns at near stations, which are consistent with the fault motion found from geological and geodetic studies. They are reproduced from Honda and Masatsuka's paper (1952) as shown in figure 9.

The phase differences between Love and Rayleigh waves for these shocks are measured by the filtering-correlation method described in Part 1. An example of the cross-correlation function for the period band 60 to 100 sec is shown in figure 9. It is clearly demonstrated that the function for shock No. 5 precedes that for the shock No. 2 by about 0.2 circle in phase, if we correct for a small difference in epicentral distance between them. This means that the value of $\phi_R - \phi_L$ is greater for

TABLE 12

SUMMARY OF FAULT SYSTEM IN THE JAPANESE SHOCKS

Shock No.	Name	Strike Direction	Dip Direction	Dip Angle	Slip Angle	Type of Motion	References
Geological and Geodetic Evidences							
2 Tottori, Sept. 10 1943	Shikano Fault West	N80°E	North	(65°)	(9°)	Right-lateral, normal, downthrow on the north side	Tsuya (1944)
	East	N80°E	Vertical	(90°)	(75°)	Right-lateral, normal, downthrow on the south side	
	Yoshioka Fault	E–W	South	(83°)	(15°)	Right-lateral, reverse, downthrow on the north side	
3 Mikawa, Jan. 12, 1945	Fukozu Fault E-W wing	E–W	South	(70°)	(65°)	Left-lateral, thrust, downthrow on the north side	Tsuya (1946)
	Fukozu Fault N-S wing	NNW–SSE	West	(70°)	(65°)	Right-lateral, thrust, downthrow on the east side	
5 Fukui, June 28, 1948		N20°W	East	(80°)	(31°)	Left-lateral, thrust, downthrow on the west side	Nasu (1950)
			Vertical	(90°)	(30°)	Left-lateral, downthrow on the west side	
			West	(80°)	(31°)	Left-lateral, normal, downthrow on the west side	
7 Longitudinal Valley, Nov. 24, 1951 (Taiwan)	Yuli Fault	N15°E	East	(85°)	(22°)	Left - lateral, thrust, downthrow on the west side	Hsu (1962) Allen (1962)
			Vertical	(90°)	(0°)	Left-lateral	
Fault Plane Solutions							
1 May 23, 1938		N31°W	N59°E	84°	90°	Pure dip-slip, downthrow on the west side	Mühlhäuser (1957)
		N31°W	S59°W	6°	90°	Pure dip-slip, downthrow on the east side	
4 April 17, 1948		N43°E	S47°E	86°	90°	Pure dip-slip, downthrow on the west side	Mühlhäuser (1957)
		N43°E	N47°W	4°	90°	Pure dip-slip, downthrow on the east side	
8 Daishoji, March 7, 1952		N21°W	N69°E	79°		Left-lateral, normal, downthrow on the east side	Ichikawa (1961)
		S70.5°W	S19.5°E	85.5°		Right-lateral, normal, downthrow on the south side	
9 Yoshino July 17, 1952		N21°W	N69°E	71.5°		Left-lateral, normal, downthrow on the east side	Ichikawa (1961)
		S75°W	S15°E	67.5°		Right-lateral, normal, downthrow on the south side	

TABLE 12—*Continued*

Shock No.	Name	Strike Direction	Dip Direction	Dip Angle	Slip Angle	Type of Motion	References
			Fault Plane Solutions—*Continued*				
11 Sept. 29, 1956		N7.5°E	N82.5°W	27°		Right-lateral, thrust, downthrow on the east side	Hodgson, Stevens and Metzger (1962)
		N17.5°W	N72.5°E	66°		Left - lateral, thrust, downthrow on the west side	
		N27°W	S63°W	25°		Left - lateral, thrust, downthrow on the east side	Ichikawa (1961)
		N1°W	N89°E	66.5°		Right-lateral, thrust, downthrow on the west side	
12 Feb. 23, 1957 (Taiwan)		N18.5°E	S71.5°E	83°		Left - lateral, thrust, downthrow on the west side	Hodgson, Stevens and Metzger
		N77°W	N13°E	57°		Right-lateral, thrust, downthrow on the south side	(1962)
13 Nov. 10 (1957)		N41°E	N49°W	85°		Right-lateral, thrust, downthrow on the south side	Ichikawa (1961)
		N43°W	N47°E	57°		Left - lateral, thrust, downthrow on the west side	
14 Nov. 12, 1958		N61°E	N29°W	39.7°		Right - lateral, thrust, downthrow on the south side	Hodgson, Stevens and Metzger (1962)
		N18°E	S72°E	58°		Left - lateral, thrust, downthrow on the west side	
15 Jan. 22, 1959		N29°E N57°W	N61°W N33°E	89° 11°		Right-lateral Left-lateral	Hodgson (1963)
			Nodal Lines Given from Near Station Data				
10 Aug. 12, 1956		N31°E N43°W				Left-lateral, normal Right-lateral, normal	The Seismological Bulletin of the Japan Meteorological Agency (former Central Meteorological Observatory)
15 Jan. 22, 1959		N83°E N44°W				Right-lateral, normal Left-lateral, normal	
16 Odaigahara Dec. 22, 1960		N81°E N37°W				Right-lateral, normal Left-lateral, normal	
17 Jan. 16, 1961		N90°E N43°W				Right-lateral, normal Left-lateral, normal	
18 Kitamino Aug. 19, 1961		N3°W N28°E				Left-lateral, thrust Right-lateral, thrust	

TABLE 13

THEORETICAL SOURCE PHASE AND AMPLITUDE OF LOVE AND RAYLEIGH WAVES IN THE AZIMUTH TO PASADENA FOR THE JAPANESE SHOCKS ON THE ASSUMPTION OF THE DOUBLE COUPLE AND THE MODIFIED SINGLE COUPLE

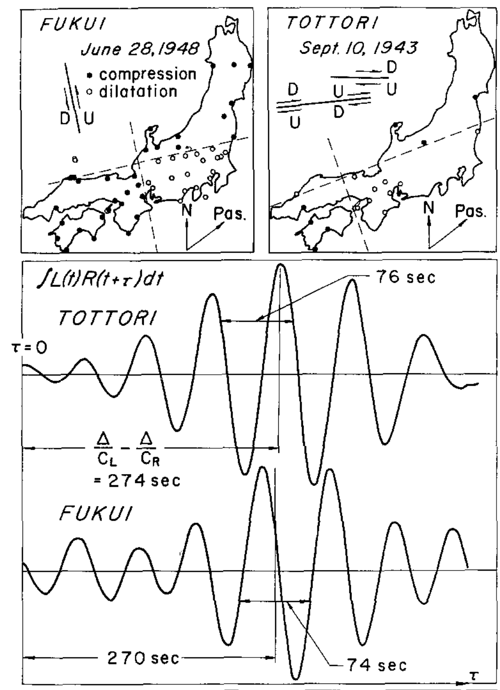
(The units of ϕ_R and ϕ_L are parts of a circle)

Shock No., Date	Type of Faulting	Depth	Modified Single Couple					Double Couple					Observed $\phi_R - \phi_L$
			A_R	A_L	ϕ_R	ϕ_L	$\phi_R - \phi_L$	A_R	A_L	ϕ_R	ϕ_L	$\phi_R - \phi_L$	
					Geological and Geodetic Evidences								
2	Shikano fault (W)	0	.63	.50	.74	.88	−.14	.45	.51	.88	.88	.00	
Sept. 10, 1943	Shikano fault (E)	0	.36	.14	.07	.87	.20	.12	.15	.88	.81	.07	
	Yoshioka fault	0	.39	.54	.89	.87	.02	.38	.53	.87	.88	−.01	
	Synthesized	0			.86	.87	−.01			.88	.87	.01	−.03
3	Fukozu fault												
Jan. 12,	E-W wing	0	.77	.19	−.46	.38	.16	.55	.29	.38	.35	.03	
1945	N-S wing	0	1.02	.19	−.44	.38	.18	.62	.14	.38	.40	−.02	
	Synthesized	0			−.45	.38	.17			.38	.37	.01	.06
5	Dip east	0	.55	.48	.03	.87	.16	.23	.50	.87	.88	−.01	
June 28,		0.2λ	.47		.12	.87	.25	.38		.11	.88	.23	
1948	Vertical	0	.63	.47	.02	.88	.14	.39	.47	.88	.88	.00	
		0.2λ	.47		.13	.88	.25	.35		.13	.88	.25	
	Dip west	0	.70	.45	.02	.88	.14	.52	.43	.88	.89	−.01	
		0.2λ	.48		.14	.88	.26	.30		.15	.90	.25	.20
7	Dip east	0	.56	.31	−.09	.38	.53	.54	.30	−.12	.36	.52	
Nov. 24, 1951 (Taiwan)	Vertical	0	.61	.35	−.12	.38	.50	.61	.35	−.12	.38	.50	.47
					Fault Plane Solutions								
1	Dip east	0	1.04	.00	.14	—	—	.16	.00	.38	—	—	
May 23, 1938	Dip west	0	1.04	.00	.61	—	—						.39
4	Dip east	0	.18	.01	.14	.87	.27	.04	.07	.38	.08	.30	
April 17,		0.2λ	.18		.11	.86	.25	.13		.09	.10	−.01	
1948	Dip west	0	.18	.07	−.39	.10	.51						
		0.2λ	.05		−.32	.11	.57						−.08
8	Left-lateral	0	.49	.54	.80	.87	−.07	.46	.54	.88	.87	.01	
Mar. 7,		0.2λ	.18		.61	.87	−.26	.08		.58	.87	−.29	
1952	Right-lateral	0	.51	.53	.95	.87	.08						
		0.2λ	.11		.15	.87	.28						−.38
9	Left-lateral	0.2λ	.34		.61	.87	−.28	.18		.69	.86	−.27	
July 17,		0.4λ	.26		.56	.86	−.30	.21		.61	.85	−.34	
1952	Right-lateral	0.2λ	.17		.15	.87	−.72						
		0.4λ	.14		.28	.87	−.59						−.38
11	Left-lateral	0.2λ	.80		.11	.86	.25	.49		.08	.89	.19	
Sept. 29,		0.4λ	.58		.09	.85	.24	.51		.04	.89	.15	
1956	Right-lateral	0.2λ	.34		.66	.92	−.26						
(Hodgson *et al.*)		0.4λ	.18		.76	.94	−.18						.15
12	Left-lateral	0	.50	.20	.96	.38	−.42	.33	.19	−.13	.34	−.47	
Feb. 23,		0.2λ			.12	.38	−.26			.12	.30	−.18	
1957	Right-lateral	0	.52	.17	.80	.33	−.53						
(Taiwan)		0.2λ			.87	.29	−.42						−.45

TABLE 13—*Continued*

Shock No., Date	Type of Faulting	Depth	Modified Single Couple A_R	A_L	ϕ_R	ϕ_L	$\phi_R - \phi_L$	Double Couple A_R	A_L	ϕ_R	ϕ_L	$\phi_R - \phi_L$	Observed $\phi_R - \phi_L$
	Fault Plane Solutions—*Continued*												
13 Nov. 10, 1957	Left-lateral	0	.39	.53	.24	.86	.38	.35	.51	.38	.86	.52	
	Right-lateral	0	.43	.50	.49	.87	.62						.11
14 Nov. 12, 1958	Left-lateral	0.2λ	.47		.10	.82	.28	.38		.07	.89	.18	
		0.4λ	.35		.10	.80	.30	.37		.05	.90	.15	
	Right-lateral	0.2λ	.13		.71	.92	−.21						
		0.4λ	.08		.86	.94	−.08						.41
15 Jan. 22, 1959	Left-lateral	0	.36	.11	.16	.78	.38	.08	.11	.37	.78	.59	
		0.2λ	.09		.12	.72	.40	.25		−.37	.72	.89	
	Right-lateral	0	.36	.09	.59	.88	−.29						
		0.2λ	.34		.63	.88	−.25						.41
	Nodal Lines Given from Near Station Data												
10 Aug. 12, 1956	Left-lateral Dip west												
	Dip = 80	0	.57	.29	.02	.37	−.35	.40	.33	.88	.35	.53	
		0.2λ	.37		.14	.37	−.23	.19		.17	.33	−.16	
	Dip = 50	0	.88	.35	.04	.37	−.33	.49	.40	.88	.37	.51	
		0.2λ	.25		.15	.37	−.22	.44		.60	.36	.24	
	Left-lateral Dip east												
	Dip = 80	0	.57	.29	.73	.38	.35	.40	.33	.87	.40	.47	
		0.2λ	.37		.61	.38	.23	.19		.58	.42	.16	
	Dip = 50	0	.88	.35	.71	.38	.33	.49	.40	.87	.38	.49	
		0.2λ	.25		.60	.38	.22	.44		.15	.39	−.24	−.25
16 Dec. 26, 1960	Left-lateral Dip north												
	Dip = 80	0.2λ	.94		.62	.87	−.25	.67		.61	.87	−.26	
		0.4λ	.69		.61	.87	−.26	.65		.59	.87	−.28	
	Dip = 50	0.2λ	.46		.60	.85	−.25	.14		.46	.84	−.38	
		0.4λ	.31		.56	.83	−.27	.26		.42	.83	−.41	
	Left-lateral Dip south												
	Dip = 80	0.2λ	.94		.13	.88	.25	.67		.14	.88	.26	
		0.4λ	.69		.14	.88	.26	.65		.16	.88	.28	
	Dip = 50	0.2λ	.46		.15	.90	.25	.14		.29	.91	.38	
		0.4λ	.31		.19	.92	.27	.26		.33	.92	.41	.34
17 Jan. 16, 1961	Left lateral Dip north												
	Dip = 80	0	.98	.14	.64	.87	−.23	.26	.17	.88	.89	−.01	
		0.2λ	.93		.62	.87	−.25	.67		.61	.90	−.29	
	Dip = 50	0	.78	.33	.67	.86	−.19	.59	.40	.88	.87	.01	
		0.2λ	.55		.60	.85	−.25	.23		.51	.86	−.35	
	Left-lateral Dip south												
	Dip = 80	0	.98	.14	.11	.88	.23	.26	.17	.87	.86	.01	
		0.2λ	.93		.13	.88	.25	.67		.14	.85	.29	
	Dip = 50	0	.78	.33	.08	.89	.19	.59	.40	.87	.88	−.01	
		0.2λ	.55		.15	.90	.25	.23		.24	.89	.35	.35
18 Aug. 19, 1961	Left-lateral Dip east												
	Dip = 80	0	.88	.09	.14	.87	.27	.19	.15	.38	.91	.47	
	Dip = 50	0	.69	.25	.16	.86	.30	.49	.39	.38	.87	.51	
	Left-lateral Dip west												
	Dip = 80	0	.88	.09	−.39	.88	−.27	.19	.15	.37	.84	.53	
	Dip = 50	0	.69	.25	.41	.89	−.30	.49	.39	.37	.88	.49	.62

shock No. 5 than No. 2 by that amount. The theoretical values of $\phi_R - \phi_L$ are shown in the same figure for the single couple, the double couple and the modified single couple model. The agreement between the theory and observation is excellent for the modified single couple and fair for the double couple. The single couple model indicates the greater value of $\phi_R - \phi_L$ for shock No. 2, and clearly fails to explain the observation.



$\phi_R - \phi_L$	S. C.	D. C.	M. S. C.
TOTTORI	.50	.01	-.01
FUKUI	.23	.12	.20

FIG. 9. Comparison of crosscorrelation function of Love and Rayleigh waves between two Japanese earthquakes. The initial motion data at near stations and the schematic picture of the faults found by geological and geodetic investigations are shown at the top. The theoretical values of $\phi_R - \phi_L$ for these shocks are also shown in parts of a circle for the single couple, double couple and modified single couple hypothesis. The values of the phase velocities C_R and C_L indicated here are shown in figure 10.

The values of $(1/C_R) - (1/C_L)$ (phase delay time difference between Love and Rayleigh waves) for the oceanic portion of the path, which gives the observed values of $\phi_R - \phi_L$ for the two shocks in agreement with the theory on the modified single couple assumption are plotted in figure 10. Since the theoretical source phase is indeterminate by the integer multiple of 2π, two curves are shown indicating the difference of 2π in the theoretical source phase. Since the lower curve tends to deviate greatly from the theoretical curves for standard oceanic structure at long periods, we choose the upper curve as the actual one. The observed curve thus determined shows a significant discrepancy either from the theoretical curve of Case 122 or that of Case 11A (Anderson and Toksöz, 1963). Those theoretical models are, however, primarily based on the observation of Love waves in these periods. If the Love wave velocity for our path is assumed to agree with the theoretical value, we expect that the Rayleigh wave velocity would be lower than the theoretical by 1 to 2% in the period range 40 to 80 sec. This suggests a strong anisotropy in the upper mantle. There is, however, another possible explanation that the wave path from Japan to Pasadena lies in a region where the upper mantle structure is considerably different from the standard oceanic structure adopted in the above theoretical models.

There are some other lines of evidence which support the observed phase delay times obtained above. Figure 11 shows the cross-correlation function between Love and Rayleigh waves for several frequency bands for shock No. 1. This shock is located in the ocean to the east of Honshu, and the wave path to Pasadena is almost entirely oceanic. As shown in the figure, the envelope of the function is very well

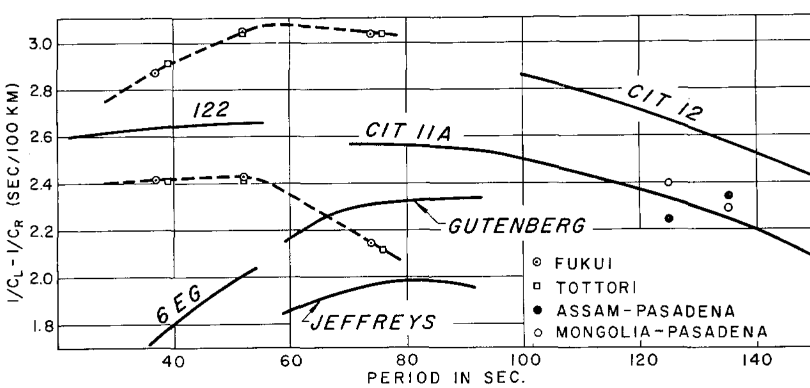


FIG. 10. Observed and theoretical phase delay time difference between Love and Rayleigh waves. The observed values obtained from the records of Fukui and Tottori earthquakes are shown by a dashed line. The observed values obtained by Toksöz and Anderson (1963) from the Pasadena records of Assam and Mongolia earthquakes are also shown. The theoretical curve for Case 122 are obtained from the results of Sykes et al. (1962), those for Case 11A and 12 are obtained by Anderson and Toksöz (1963), and those for the Gutenberg and Jeffreys models are by Takeuchi (1963).

defined, and we can get a reliable arrival time of the peak of the envelope, which gives the group delay time difference between Love and Rayleigh waves. We found that their values for various periods agree with those expected from the observed phase delay time difference shown in figure 10.

Further, the propagation correction based on the above phase delay time data gives a very good agreement between the theory and observation for shocks No. 3 and No. 7, for which we also have evidences of faults found by geological studies. The source phase and amplitude of Love and Rayleigh waves are computed in the same way as before. The fault parameters are given in table 12, and the results of computation are listed in table 13. The observed values of $\phi_R - \phi_L$ are obtained by the use of the propagation correction determined above, and are compared with the theoretical values in figure 12. The agreement is satisfactory either for the double couple model or the modified single couple model, and strongly supports the validity of our propagation correction.

The measurement of the source phase difference $\phi_R - \phi_L$ was done by the filtering-correlation method and by the stationary phase method. The results are shown in table 14 and 15. There is a satisfactory agreement between the values obtained by the two methods for the same shock.

We shall now consider the shocks for which fault plane solutions are given from initial motion data. The solutions are listed in table 12, and the source values of Love and Rayleigh waves in the azimuth to Pasadena corresponding to them are given in table 13. The theoretical and observed values of $\phi_R - \phi_L$ are compared in

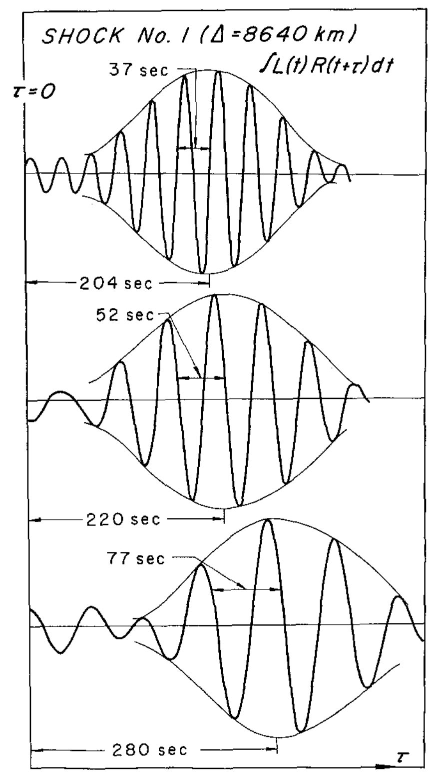


FIG. 11. Crosscorrelation function between Love and Rayleigh waves for various frequency bands. The time of the peak of the envelope gives the group delay time difference between the two waves.

figure 12 for the double couple model and the modified single couple model. Both models give equally fair agreement, and this result alone seems not to allow us to choose between the two hypotheses. The agreement is poorer than was the case for the Mediterranean shocks, where excellent agreement was obtained on the hypothesis of a modified single couple. The writer feels that this may be due to the less accurate fault plane solutions given for Japanese shocks. (We notice that if we only adopt Hodgson's solutions in figure 12, the agreement is good for the modified single couple model.) We may find the accuracy of the solutions by comparing the results of different authors on the same earthquake.

For example, Balakina *et al.* (1960) give the maximum pressure axis for shock No.

8 which is different from the one obtained by Ichikawa (1961) by 40 degrees in the azimuth. According to Mühlhäuser (1957), shock No. 1 is a pure dip-slip and the fault strike is perpendicular to the direction to Pasadena. This source cannot generate Love waves in the direction to Pasadena on either hypothesis. However, Love waves are clearly recorded from this shock at Pasadena. This suggests that there was at least a small strike-slip motion on the fault. Mühlhäuser (1957) also attributed a pure dip-slip to shock No. 4. This may be also an oversimplification.

The present study includes four other shocks for which the nodal lines of initial motions are clearly defined from near station data. As in the case of the Kern County aftershocks, we assumed that the nodal lines approximately represent the strikes of fault planes and computed the source values of Love and Rayleigh waves for different dip angles. The results are shown in table 13 for left-lateral solutions. The variation of $\phi_R - \phi_L$ with the dip angle is rather small for these cases. The values for the right-lateral solution also fall in about the same range as for the left-lateral solution, and they are not listed. The comparison of theoretical and observed values of $\phi_R - \phi_L$ for these shocks is also shown in figure 12. Again, a fairly good agreement is obtained between the theory and observation, either on the double couple assumption or on the modified single couple assumption.

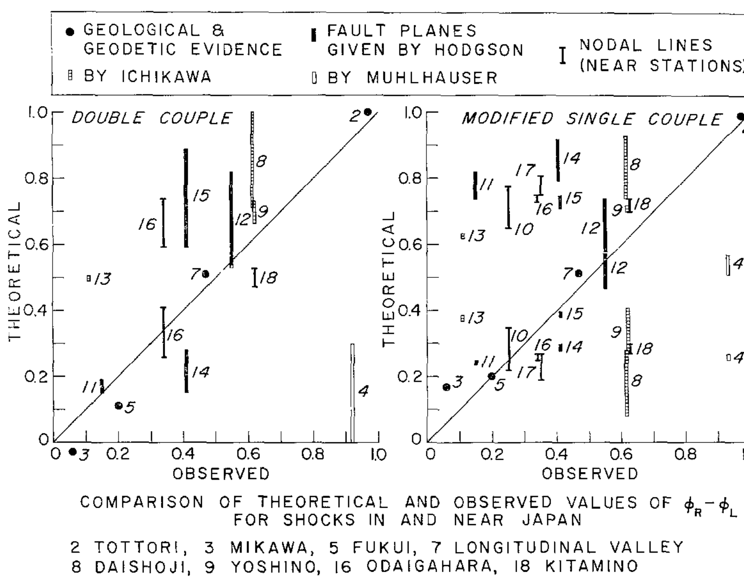


FIG. 12. Comparison of theoretical and observed values of $\phi_R - \phi_L$ for the Japanese shocks on the assumption of the double couple and the modified single couple. (The units are parts of a circle.) The numbers correspond to those shown in table 11.

Although we could not determine conclusively whether the modified single couple or the double couple is the appropriate force system for these shocks, it will be interesting to see which of the two planes of fault plane solution will be chosen as the actual fault under the hypothesis of the modified single couple. Figure 13 shows the preferred fault system on a map. It is remarkable that the preferred strike directions are mostly perpendicular to the trend of Honshu Island, and the lateral motion on the fault is all left hand. This surprisingly consistent picture of tectonics obtained by assuming the modified single couple hypothesis is perhaps a good argument in favor of the hypothesis. This result emphasizes the importance of the famous Neo-Valley fault in the Mino Owari earthquake of 1891, which was one of the biggest earthquakes in Japan. It was characterized by a fault striking perpendicular to the Island and left-lateral motion. It is interesting to compare the present result with the tectonics of the other circum Pacific regions. In California, the faults parallel to the coast are right-lateral, and those perpendicular to the coast are left-lateral. This is consistent with our results in Japan, although California is dominated by major active faults parallel to the coast, which have no known analogy

TABLE 14

OBSERVED VALUES OF $\phi_R - \phi_L$ FOR THE JAPANESE SHOCKS DETERMINED BY THE FILTERING-CORRELATION METHOD

(in parts of a circle)

Shock No.	Date						Average
1	May 23, 1938	T (sec)	37	53	77		
		$\phi_R - \phi_L$	.30	.49	.39		.39
2	Sept. 10, 1943	T	39	52	76		
		$\phi_R - \phi_L$	−.05	.00	−.03		−.03
5	June 28, 1948	T	31	37	52	74	
		$\phi_R - \phi_L$	.21	.22	.17	.20	.20
8	March 7, 1952	T	30				
		$\phi_R - \phi_L$	.50				.50
9	July 17, 1952	T	30	38			
		$\phi_R - \phi_L$	.63	.68			.66
14	Nov. 12, 1958	T	34	45	62		
		$\phi_R - \phi_L$	.44	.44	.35		.41
16	Dec. 26, 1960	T	31	38			
		$\phi_R - \phi_L$	.35	.34			.35

in Japan. On the other hand, in the Philippines-Taiwan region, the motion is left-lateral on the major faults which run parallel to the trend of islands (Allen, 1963). For example, the Longitudinal Valley earthquake (shock No. 7) shows left-lateral motion as in most of Japanese shocks studied in this paper, but the associated fault strike is clearly parallel to the local arc structure rather than cutting across it. Dr. C. R. Allen suggested to the writer that since many arc structures intersect in Japan, our results may be taken as consistent with those in the Philippine-Taiwan region if we assume that the faults of our earthquakes are related to those arcs perpendicular to the Japanese Islands.

For those shocks for which only nodal lines are known from the near station data, we cannot choose the actual faults between the two nodal lines. However, we can tell the sense of the vertical motion in two of the quadrants as shown on the map in figure 13. The motions at the other two quandrants are indeterminate.

It is remarkable that the vertical motion is almost always upward on the east side of the faults for the shocks occurring in and near the Pacific ocean. However, the pattern becomes very complicated for the shocks occurring within the Island.

TABLE 15

Observed Values of $\phi_R - \phi_L$ for the Japanese Shocks Determined by the Stationary Phase Method

(in parts of a circle)

Shock No. Date	T, sec								Average
	30	32	34	36	38	40	42	44	
3 Jan. 12, 1945	.23	.19	.12	.08	.02	−.02	−.05	−.07	.06
4 April 17, 1948	−.06	−.09	−.09	−.06					−.08
5 June 28, 1948	.17	.22	.18	.22	.18	.15	.12		.18
6 Oct. 22, 1951	.10	.09	.18	.28	.32	.38	.36		.24
7 Nov. 24, 1951	.37	.38	.38	.44	.50	.53	.55	.57	.47
8 March 7, 1952	−.43	−.34							−.38
9 July 17, 1952	.57	.56	.59	.61	.66	.67	.69		.62
10 Aug. 12, 1956	−.16	−.22	−.21	−.25	−.26	−.28	−.29	−.34	−.25
11 Sept. 29, 1956	.10	.13	.18	.17	.16				.15
12 Feb. 23, 1957	.30	.38	.44	.58	.61	.68	.69	.73	.55
13 Nov. 10, 1957	.10	.09	.12	.14	.10				.11
15 Jan. 22, 1959	.40	.41	.44	.39	.39				.41
16 Dec. 26, 1960	.30	.31	.35	.33	.34	.38			.34
17 Jan. 16, 1961	.27	.34	.35	.39	.42				.35
18 Aug. 19, 1961	.60	.63	.62	.61	.63				.62

For example, the sense of vertical motion is opposite for shock No. 5 and No. 8 and also for shock No. 9 and No. 16. Each of these pairs occurred in nearly the same area, and shows almost identical initial motion pattern at near stations. However, the surface wave evidence requires opposite vertical motion for each pair. This may be a manifestation of a scissoring phenomenon, which is a rather common feature associated with strike-slip faulting (Richter, 1958). It should be noted that shock No. 8 followed No. 5 after four years, and shock No. 16 followed No. 9 after eight years.

Comparison of Theoretical and Observed Amplitude Ratio of Love to Rayleigh Waves

So far we have not given much attention to the amplitudes of Love and Rayleigh waves. This is primarily because the amplitudes are more sensitive to the source parameters of earthquakes such as the dip angle of the fault plane, the slip direction

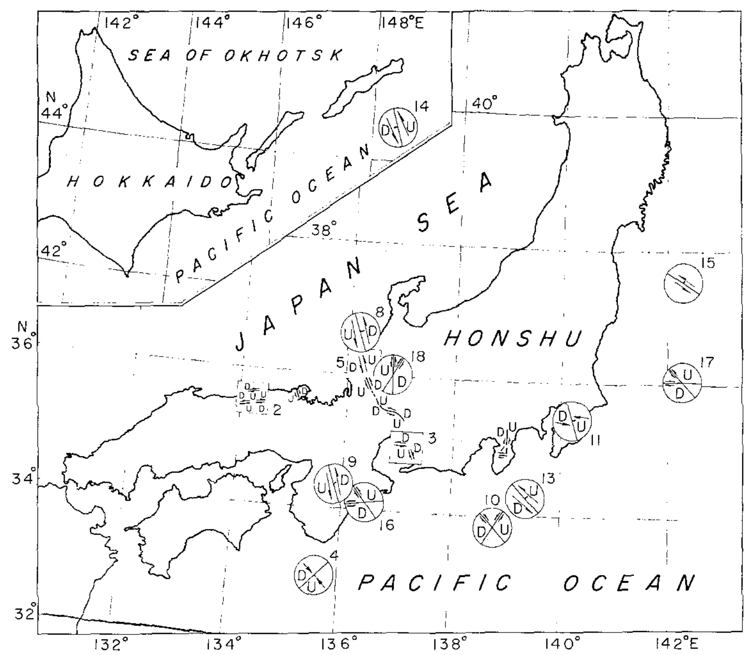


Fig. 13. Fault plane solutions determined with the aid of surface wave evidence on the assumption of the modified single couple. (They are indicated by the circle with one fault strike, see figure 4.) The circle with two fault strikes corresponds to the shocks for which nodal lines of P waves are known only at near stations. The fault in a square corresponds to the shocks with known faulting. The numbers in this figure refer to those shown in table 11. The faults observed in the Mino-Owari earthquake of 1891 and in the Izu earthquake of 1930 are also shown.

and the azimuth to the recording station. Also, the depth of focus and the layering of the earth's crust in the focal region affect the amplitudes more seriously than the phases. Hence, we need greater accuracy of information on these source parameters than in the study of phases.

Figure 14 shows a comparison of theoretical and observed amplitude ratio of Love to Rayleigh waves for the shocks having very shallow focal depths. The observed ratio is the ratio of the maximum total displacement of Love waves to the maximum vertical displacement of Rayleigh waves. The periods of waves are in the range from 30 to 40 sec for the Japanese shocks, and 40 to 60 sec for the Mediterranean shocks. The instrument used is the Benioff long period seismograph (T_0 = 1 sec, T_g = 90 sec) at Pasadena.

The theoretical values shown in figure 14 are obtained from the amplitude values given in table 3 and 13. Those for the modified single couple model correspond to the solutions preferred on the basis of the phase measurement. As can be seen in the above tables, there are only slight difference in the amplitude values between the preferred solution and the discarded ones. It is practically impossible to discriminate between them on the basis of amplitude measurement alone.

Despite the difficulties with amplitudes as mentioned before, figure 14 shows a strong correlation between the theoretical and observed amplitude ratios, the error being about a factor of 2. This result supports our fundamental assumption that the source of short period body waves, on which the fault plane solutions are based, is also the source of the long period surface waves.

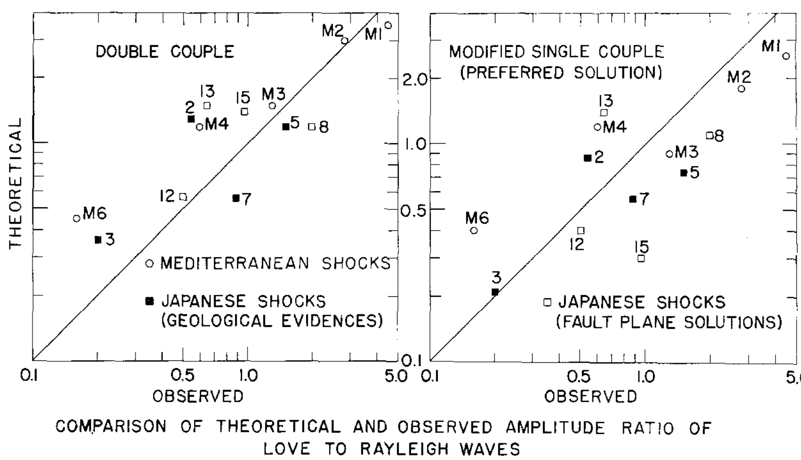


FIG. 14. Comparison of theoretical and observed amplitude ratio of Love to Rayleigh waves on the assumption of the double couple and the modified single couple. The numbers in this figure refer to the shock numbers given in table 1 and table 11.

The agreement between theory and observation is equally fair for the double couple and the modified single couple hypothesis, and we cannot choose the right one on the basis of this evidence.

As described in Part 1, the theoretical amplitude ratio is normalized in such a way that the ratio is unity for the maximum amplitude of Love and Rayleigh waves from pure strike-slip on a vertical fault. The fair agreement between the theory and observation shown in figure 14 indicates that this normalization happens to be consistent with the actual phenomenon. Recently, Harkrider (1963) made a detailed theoretical study on the excitation of Love and Rayleigh waves for a layered media and showed that the amplitude ratio of Love to Rayleigh waves is 1.2 to 1.8 for the strike-slip vertical fault using Gutenberg's continental earth model.

SUMMARY AND CONCLUSION

The basic assumptions underlying the surface wave method of the earthquake mechanism study have been examined by investigating these waves from earthquakes with known faulting and/or fault plane solutions. Since the single couple hypothesis fails to explain observations, we proposed a modification of this hypothesis. The new hypothesis explains observation very well, and offers a method to choose the actual fault from the two planes of the fault plane solution. The double couple hypothesis is also examined, and was shown to explain observation generally poorer than the modified single couple hypothesis.

Surprisingly consistent pictures of tectonics in the Mediterranean region and in Japan (figure 5 and 13) obtained on the basis of the modified single couple hypothesis also support indirectly the validity of the hypothesis.

The new hypothesis must be examined theoretically. Theories based on slip dislocation seem to favor the double couple as the equivalent force system of an earthquake. However, it is not unlikely that if the effect of the free surface on the dislocation is fully studied, the theory may eventually favor the modified single couple rather than the double couple. We presume that the new hypothesis will only apply to long period surface waves from shallow shocks, because the effect of the free surface would be significant only for these waves.

The present study also provides some information on the structure of the earth. It was shown that the phase velocity data based on the standard oceanic and continental structures are applicable to the wave path from Pasadena to the eastern Mediterranean region. A small modification of the standard structure was required to explain observation for the path from California to the east coast of North America. A significant modification of the standard structure was required for the oceanic path between Japan and Pasadena.

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Dr. Frank Press and Dr. Clarence R. Allen kindly read through the manuscript and gave the author valuable suggestions and advice.

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